Influence de l'endommagement matriciel sur la résistance en compression sens fibre pour des composites stratifiés

Matrix damage influence on compressive failure in composite materials

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Résumé

L'étude expérimentale proposée ici vise à caractériser le comportement d'un composite tissé verre/epoxy et d'étudier l'influence de l'endommagement matriciel sur ses propriétés à rupture en compression. Tout d'abord, des résultats sur l'influence de l'endommagement matriciel sont rappelés. Ensuite, le comportement en compression du matériau non endommagé est étudié en réalisant des essais de flexion quatre points et de compression normalisés (ASTM-D695). Dans un second temps, une campagne d'essais à haute température permet de montrer l'effet de la dégradation thermique de la matrice sur la résistance sens fibre. Enfin, l'effet de l'endommagement sur la rupture en compression est étudié.

Abstract

The present research focuses on the identification of the compressive behavior of a woven glass/epoxy composite and the influence of matrix damage on its compressive strength. First results concerning the influence of matrix damage on composite failure properties are reminded. In the following part the behavior of the glass/epoxy composite is identified via four-points flexion tests and standard compressive tests (ASTM-D695). Then, the results of high temperature flexion tests are presented to highlight the influence of matrix damage on compressive strength in fiber direction. Finally, effect of transverse damage on compressive strength is studied.

Mots Clés : Fibres de Verre, Compression, Endommagement, Flexion quatre points
Keywords : Glass fibers, Compression, Damage, Four-points bending test

1. Introduction

Matrix degradation is an important factor for the assessment of fiber reinforced polymers composites failure behaviour. In the case of tensile failure, it was shown by Hochard et al. [1], Thollon [2] and Gibson [3] that high levels of mechanical (Fig. 1.a) or thermal (Fig. 1.b) matrix degradation generate a fall of tensile failure stress to a threshold equal to the resistance of fibers alone. In the case of compression, it is easy to speculate that no stress threshold exists, when thermal or mechanical degradation is extensive the retaining action of the matrix on the fibers isn't any more possible and fiber instability and failure occurs as soon as a compressive load is applied. Rosen [4] and Budiansky [5] propose models to estimate compressive failure stress, the two hypothesize different mechanisms at the base of compressive failure but for both compressive stress failure is directly proportional to the matrix shear modulus.

According to Rosen, elastic fiber buckling is the cause of compressive failure and his model considers volumetric fraction of fibers (v_f):

$$\sigma_{min} = \frac{G_m}{1 - v_f} \approx G_{12} \tag{1}$$

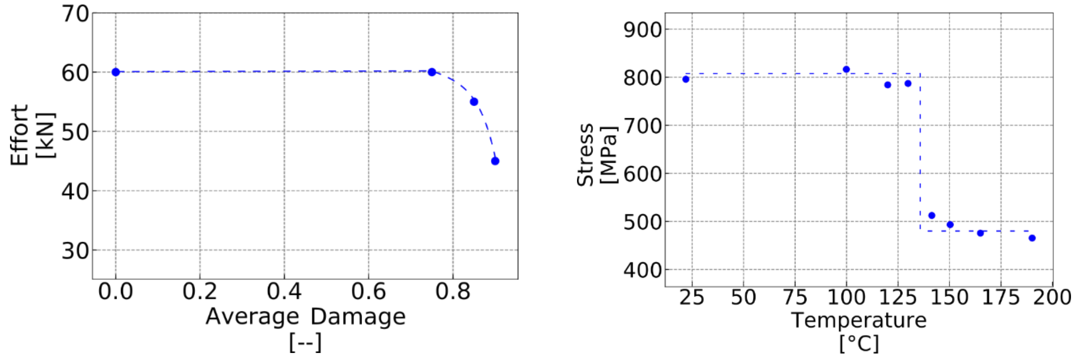
Budiansky puts plastic fiber kinking at the base of his model and takes into account fiber initial misalignment ($\bar{\varphi}$) and matrix shear yield strain (γ_Y):

$$\sigma_{min} = \frac{G_{12}}{1 + \bar{\varphi}/\gamma_Y} \tag{2}$$

Coupling these models with continuum damage mechanics [6] definition of ply damage as a loss of stiffness, $d_{12} = 1 - G_{12}/G_{12}^0$, we can show theoretically how matrix shear damage (d_{12}) directly influences compressive failure:

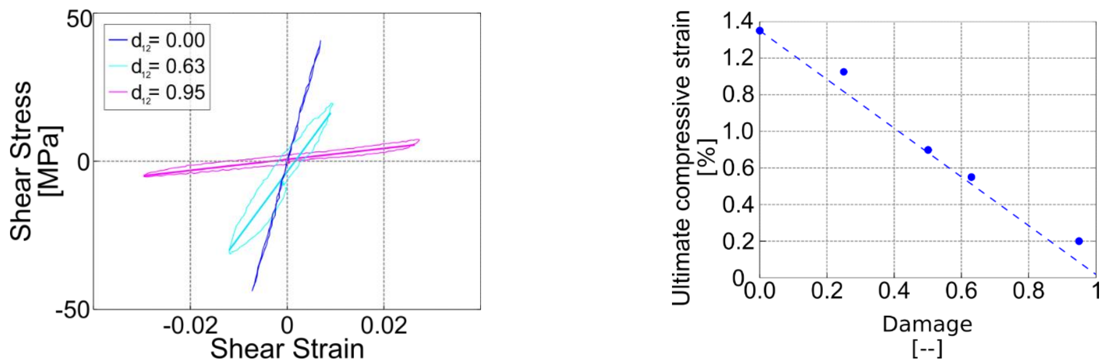
$$\sigma_{min} = G_{12}^0(1 - d_{12}) \tag{3}$$

Because this simple equation is not predictive at ply scale, this strong influence was studied by Eyer [7],[8] in the case of mechanical damage. Eyer [8] uses almost the same procedure as Thollon [2]. Using carbon/epoxy tubular samples, the matrix is firstly damaged in shear by torsional loads (d_{12}) (Fig 2a). Then, compressive tests are carried out and show a large decrease of strength in presence of damage (Fig 2b). Gibson [3] and Feih [9] studied the effect of thermal degradation and confirm that high levels of damage result in very low compressive resistance of samples.



(a) (b)

Fig. 1. Effect of damage on tensile strength: a); b) Tensile failure stress vs. temperature on a GFRP 1055/ES18 [2]



(a) (b)

Fig.2. Effect of damage on compressive strength: a) shear damage on tubular samples b) compressive failure strain vs shear damage [8]

In order to accomplish the aim of characterize compressive behaviour we have chosen to carry out four-point bending and compressive tests following the prescriptions of ASTM-D695. As reported by Woolstencroft [10], Harper et al. [11] standard compressive tests tend to underestimate strength of composites, Kim et al [12] emphasise this problem in the case of glass/epoxy composites tested under ASTM-D695 standard. Because of this reason bending tests are used to characterize compressive behaviour of composite materials. Three kind of bending tests are normally used, pure bending [13], three-points [14], four-points [15]. Flexion tests present complications linked to large displacements and rotation that make difficult calculation of the sample's stress field. On the other side samples geometry is simpler and gauge area is more extensive than the one prescribed in compressive tests avoiding stress concentration problems that could lead to premature failure. Because of these reasons we opted to carry out both the typologies of tests and to compare their results. Then, high temperature tests were performed in a thermal enclosure to study the effect of matrix thermal degradation. Finally, effect of transverse damage on compressive strength is studied.

2. Mechanical tests

Mechanical tests were conducted on a MTS1000 universal testing machine, strain measures were performed mainly via 2D and 3D direct image correlation (DIC) via ARAMIS software, strain gauges were only used to validate DIC measures in the preparation phase of the tests. To optimize the geometry of samples FEM analysis was conducted on ABAQUS software. The goal of the geometry optimization was to obtain a shape that granted a stress field as homogeneous as possible in the central part of the avoiding stress concentration that could lead to premature failure of the samples.

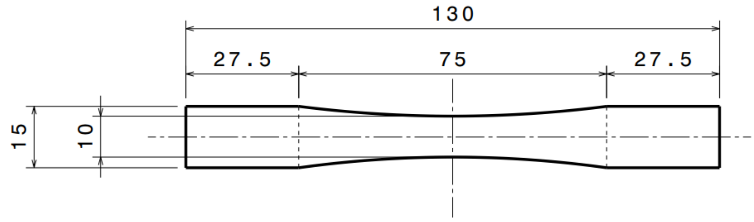


Fig. 2. Dumbbell Sample Geometry

The material for our study is an Epoxy matrix glass fiber reinforced woven composite produced by Hexcel (Hexcel M42ST/1055). The main characteristic of this woven is to be unbalanced with 83% of the fibers in wrap direction and only 17% in weft. This material has been chosen because the 17% fibers in transverse gives the ability to reach high level of matrix damage in transverse direction without premature fracture [2]. Press moulding at 150°C for 5h at a pression of 5bar is the recommended cure cycle. Due to impossibility to perform press moulding process we opted for an autoclave process and increased the cycle pressure to 7 bar. Finally, we were able to obtain plates with a final ply thickness of 0.33mm when the recommended thickness was 0.29mm.

All specimens were obtained by water-jet cutting from 14 plies plates for a thickness of 4.6 mm (fiber volume fraction around 57%). The main constraint on the thickness of the specimens came from the necessity to do not exceed the load limit of the flexion rig (800 N). Thicker specimens would have performed better in compression, due to higher resistance to buckling, but would not have broken in bending. The same samples were used for both compressive and bending tests as the designed shape is not far the one prescribed by ASTM-D695.

Preparation of damaged samples

To obtain damaged samples the same technique used by Eyer [7] and Caous [16] was implemented. Small samples were cut-out from a large plate damaged by cyclic loading. Differently to Eyer and Caous, that used $[+45, -45]_{ns}$ layups generating shear damage, we choose a $[90]_{14}$ layup to induce only transverse damage (taking advantage of the 17% of fibers in weft) and avoid fibre re-orientation. Dimension of the plate were 140mm x 600mm for a thickness equal to 4.6mm. Extremities of the plate were reinforced thanks to glued tabs. A custom rig was used to position the plate in the machine jaws and to ensure uniform transmission of the effort to the plate. To keep track of the damage level static load cycles were regularly performed each 500 cycles to measure the stiffness of the plate and calculate damage level. 2D DIC was used to calculate local damage values on the surface of the plate. The final result was a level of layup damage in the range of 25% to 40% in the central part of the plate (Fig. 4).

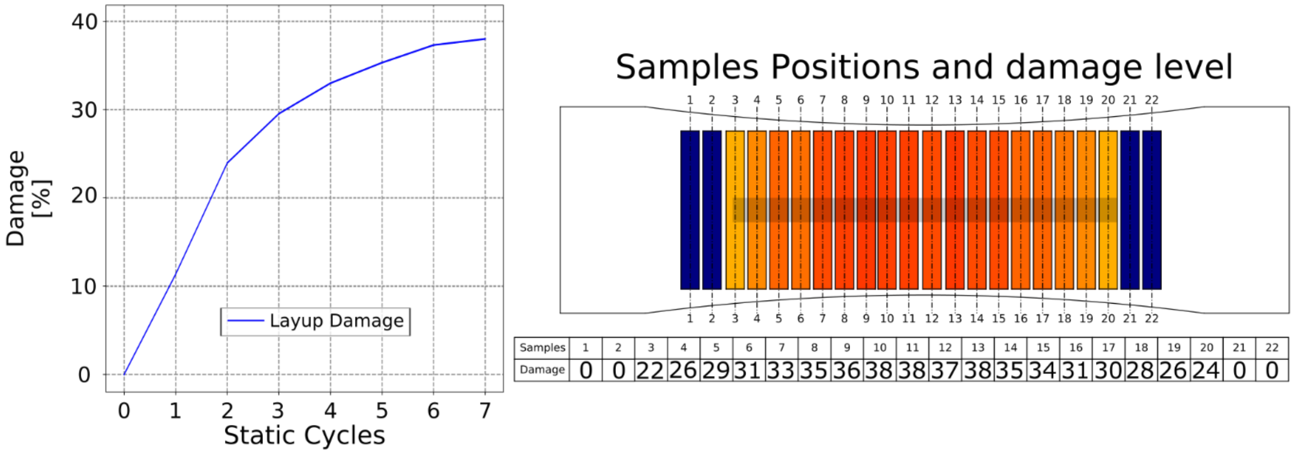


Fig. 4. Damaged samples

2.1 Room Temperature bending tests

The main purpose of bending tests was to characterize the material's compressive behavior in presence of a uniform stress/strain field avoiding buckling of the specimens. A four-points bending rig was used. FEM simulations were conducted on ABAQUS to optimize rig configuration. Finally, distance between the upper rollers was fixed at 50mm and at 80mm for the lower ones.

One of the problems of bending testing is given by large rotations of the sample under the loading conditions. During a test position of contact points constantly changes together with force effective component's direction, consequentially magnitude of the moment is not directly proportional to applied force. This means that a correction must be applied to estimate the real magnitude of the moment imposed on the sample. The corrected value was obtained as function of rig's upper part displacement. Strains were measured via 2D direct image correlation (DIC) on one side of the samples. Measure of compressive strain via gauges resulted impossible due to surface mesh micro buckling (see. paragraph 2.3) leading to delamination of the gauge in the conclusive part of the tests. To calculate local strain measure starting from the strain field generated by DIC an averaging procedure was applied. Strain field was measured on sample's side central part on a 10 mm x4.6 mm gauge surface. First the strain values were averaged lengthwise on multiple rows to obtain their thickness-wise distribution. Contrary to what has been observed for carbon/epoxy materials in literature [13], [15], from this first average, we could already appreciate the linearity of the behavior because flexion's neutral axis remained at the center of the section denoting a thickness-wise symmetric distribution of strains and by consequence of stresses. Strains on top and bottom surfaces were obtained via extrapolation from the values obtained from the bulk part of the specimen and compared to the ones measured by the gauges to validate the averaging procedure.

All samples, damaged and un-damaged, broke in the central part in traction. The only compression linked phenomenon that we were able to notice was localized buckling of woven interlocks. This phenomenon was limited to the interlocks, the rest of the surface did not present any signs of compressive failure or surface buckling. Results of the tests showed how the material presented linear behavior both in compression and in traction. The average ultimate stress was 837±30 MPa, tensile strain was 3.18±0.13 %. Young modulus averaged at 28±0.61 MPa.

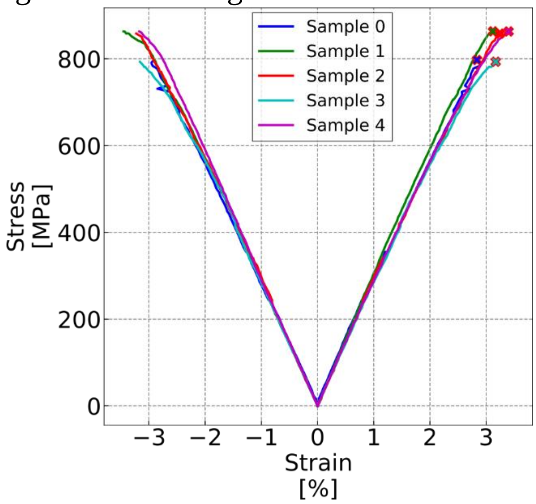


Fig. 5. Flexion tests results

2.2 High temperature flexion tests

To test the hypothesis that layup compressive strength is tightly linked to matrix degradation we have chosen to realize the same four points bending tests but increasing temperature starting from 80°C and up to 180°C (curing temperature of the matrix is 150°C). As temperature increased matrix stiffness decreased resulting in a loss of samples stiffness. Compressive failure did not appear until 100°C for a stress slightly above 500 MPa. Starting from 120°C only compressive failures were observed (Fig. 7). Increasing temperature up to 180°C compressive failure occurred for decreasing levels of stress down to 200 MPa, no thresholds appeared confirming the assumption that for high levels of matrix degradation compressive strength tends to zero.

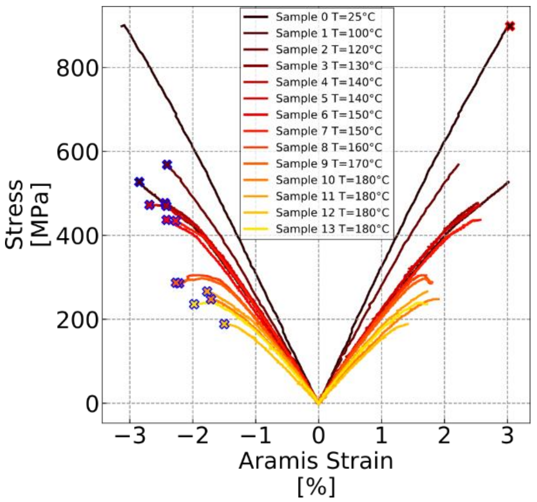


Fig. 6. High temperature Flexion tests results

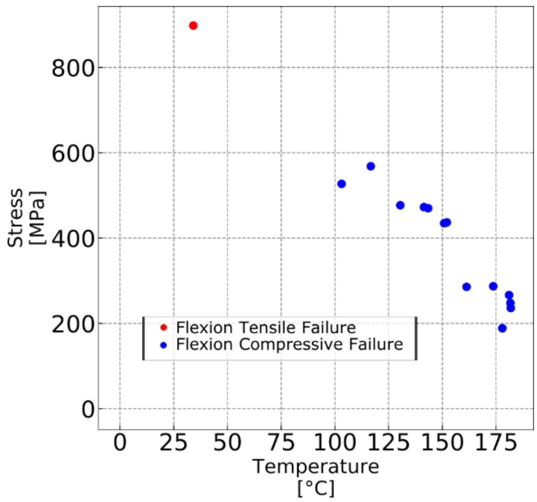


Fig. 7. High temperature flexion tests failures

2.3 Compressive Tests

Two kind of compressive tests were performed. A first group of samples was tested by positioning them directly in the machine jaws. DIC was utilized to measure strain fields of the samples, two cameras were deployed to measure the full 3D displacement/strain field, this enabled us to keep track of out-of-plane displacements. Tests on a second group were conducted using an ASTM-D695 testing rig, longitudinal strains were measured using 2D image correlation on the side of the samples due to the geometry of the testing rig that inhibits access to the faces of the specimen.

Not using a specialized testing rig for compression tests resulted in the problem that buckling was always present even when the sample's free-length was reduced do 30 mm, due to misalignment of the sample in machine's jaws or/and small misalignment of the jaws themselves. However, it made possible to measure the strain field of the full surface, operation impossible on a sample as constrained as in a compression rig. Due to the unpredictable nature of buckling instability and the possibility to measure strains only on one surface it was impossible to determine the failure strain of the samples where failure occurred on the face opposite to the camera's objective. Nevertheless, samples' stress field at failure is of complicate determination due to the simultaneous presence of compression and buckling induced flexion.

Tests were conducted decreasing sample's free-length from 60 mm until failure load stopped depending on free-length as proposed by Eyer for tubular specimen in [ref sur les tubes en compression Comp Part A]. It was obtained that starting from 35 mm failure load remained constant also for a free-length of 30 mm, we interpreted this result as failure was due only to material properties (Fig. 8). Failure load for these last samples was close to 29 kN (in absence of buckling this would translate to a stress around 630 MPa) and out of plane displacement (measured via 3D DIC) were negligible, although strain fields were not homogeneous (Fig. 9) meaning that buckling generated bending and out-of-plane phenomenon were still present. Minimal strain recorded during these tests was -3.2%, independently of free-length, in correspondence of the failure zone right before collapse (Fig. 9).

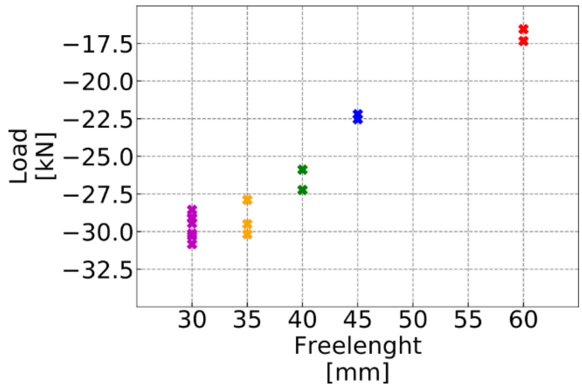


Fig. 8.Compressive tests Results

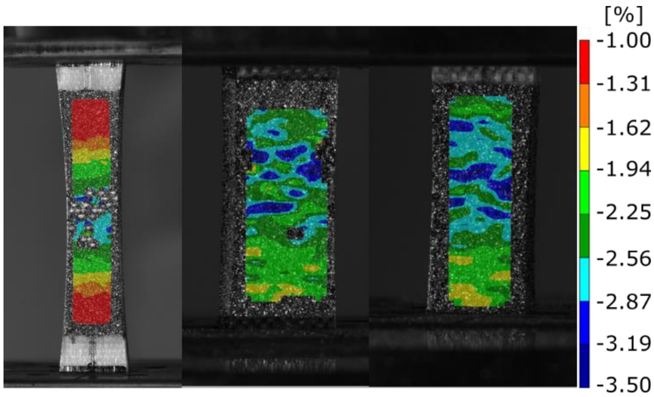


Fig. 9. DIC strain fields for 60mm, 30mm, 35mm free-length samples

Tests conducted following ASTM-D695 standard resulted in failure of the sample far from central zone and close to the stress concentration zone. These samples failed for a stress level around 700 MPa with a minimum longitudinal strain around -2.45% (Fig. 10). Presence of diffuse damage is noticeable on samples' central part (Fig. 11) and an even greater presence of damage is noticeable close to failure zone. Dumbbell samples (Fig. 3) were also tested using ASTM-D695 rig. These samples failed at 790 MPa with a minimum longitudinal strain of 2.9%. Failure occurred in the central part of the specimen but not in the middle where highest stresses should be present. Damaged samples failed at 700 MPa .

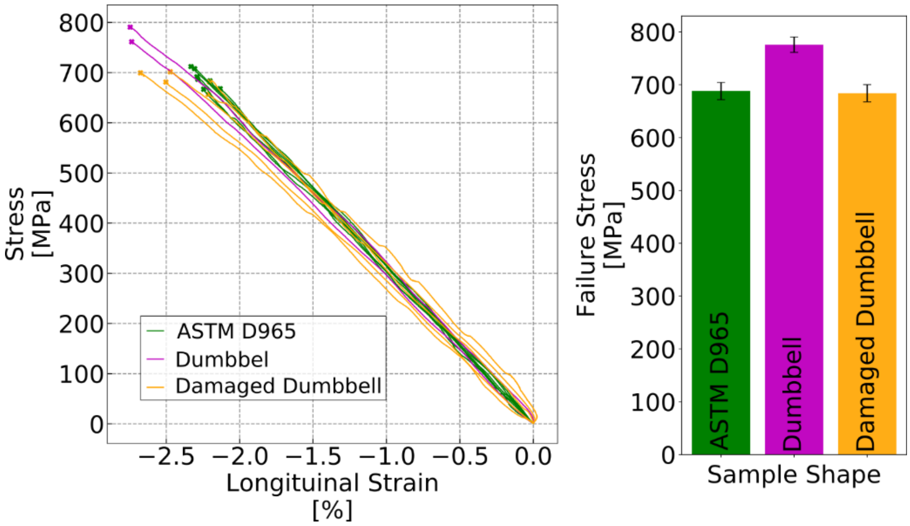


Fig. 10. ASTM-D695 Results

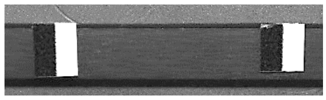


Fig. 11.a sample at the beginning of the test

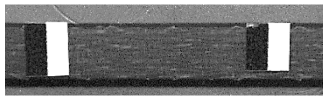


Fig. 11.b. sample at the end of the test

Fig. 11. ASTM-D695 sample damage evolution

3. Discussion

To study compressive behaviour up to failure of an Epoxy/Glass composite (Hexcel 1055/N42ST) we conducted four-points bending and compressive tests. First remarkable result is that compressive behaviour was identified as linear contrary to what is normally found for carbon fibers [17],[13],[15]. Second, no compressive failures were observed even for stresses close to 840 MPa due to all samples failing in traction. These first tests highlighted how glass fibers present compressive stress failure at least equal to tensile one. Damaged samples tested in flexion did not present any difference to un-damaged samples. We can hypnotise that due to the fact that only the most outer plies are subjected to the highest stresses even if these start to fail part of the load is redistributed to the other plies and this mechanism avoids catastrophic failure.

Compressive tests carried out without special rigs seem to confirm that compressive failure occurs for strains lower than -3.2%, a level that was not reached in bending due to tensile failure. ASTM-D695 compressive tests confirmed behaviour's linearity but prescribed samples always failed due to stress concentrations in proximity of an area where influence of both compressive and shear stress was remarkable. This led to compressive failures at 700 MPa. Higher stress failure reached in bending tests can be justify by the presence of a thickness-wise stress gradient as explained by Wisnom [18],[19]. ASTM-D695 compression rig vas also utilised on samples with the dumbbell geometry presented in Fig. 3. These samples failed at 790 MPa confirming that the new samples geometry grants a more homogeneous stress field getting closer to pure material failure. To better comprehend the influence of sample geometry in compression FEM simulations were done on ABAQUS software utilising the damage model developed by Hochard *et al.* [6],[20],[21] . Results of the simulations superposed to images of the broken samples (Fig. 12) highlight how failure occurred in zones where compressive stresses were elevated but damage was also present. This is particularly evident in the case of the modified sample (Fig. 12.b) where stress in the central part is homogeneous, but failure occurred where compressive stress and damage were both present (Fig. 12.b). Damaged samples tested on the ASTM-D695 rig failed at 700 MPa loosing close to 100 MPa respect to un-damaged ones. Damaged samples failed in the same area as un-damaged, closer to the centre.

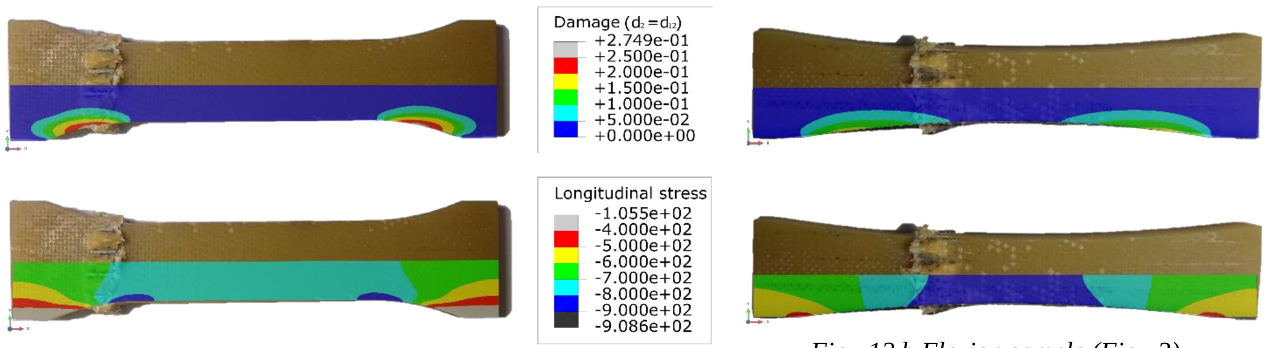


Fig. 12.a ASTM-D695

Fig. 12.b Flexion sample (Fig. 3)

Fig. 12. ASTM-D695 samples vs FEM simulation

Finally, thermal matrix degradation was studied via high temperature four-points flexion tests. Compressive failures started occurring for temperatures above 100°C (while matrix curing temperature in 150°C) at 550MPa. Temperature vas increased up to 180°C and failure stress decreased to 250Mpa. No thresholds appeared for compressive stress confirming what was found by Feih [9] confirming the strong influence of matrix degradation on compressive failure.

4. Conclusion

Compressive behaviour of a Glass/Epoxy composite (1055/N42ST) was studied. Four-points bending tests were chosen to avoid problems generated by standard compressive tests. Behaviour was identified as linear both in compression and traction. This result was confirmed by ASTM-D695 compressive tests. Compressive failure was achieved for stresses around 790 MPa on an ASTM-D695 compression rig with a modified sample (standardised samples broke at 730 MPa), FEM simulations taking into account ply damage highlighted that compressive failure occurred in zones were both damage and compressive stress were present. Compressive failure was never achieved in room temperature bending tests, this coupled with the results of pure compressive tests lead us to the conclusion that ultimate compressive stress is close to ultimate tensile failure. Compressive tests on damaged samples with a level of damage up to 40% sown a reduction of compressive strength around 12%, this decrease seems to show a difference between carbon and glass reinforced composites as compressive strength of the latter seems to be less sensible to damage level. In a second part high temperature four-points bending tests were carried out. Samples started failing in compression for temperatures above 100°C for a stress of 500 MPa and at 180°C for a stress around 200MPa. This result confirms the strong link between compressive resistance and matrix degradation

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